BELOW-AMBIENT AND CRYOGENIC THERMAL TESTING

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OUTLINE

BELOW-AMBIENT / MOTIVATION FOR CRYOGENIC TESTING
STANDARDS FOR BOILOFF CALORIMETERY
THERMAL PERFORMANCE DATA
COLD PIPE TESTER
FUTURE PLANS

ENERGY MEASUREMENT

- ENERGY GOING = POWER = HEAT FLOW RATE
- JOULES PER SECOND = WATTS
- ENERGY (JOULES) IS AN ABSTRACTION, SO WE HAVE TO MEASURE SOMETHING ELSE
- ELECTRICAL RESISTANCE
- PHASE CHANGE OF A SUBSTANCE

BOILOFF CALORIMETRY

- CRYOGENIC BOILOFF CALORIMETRY
  - STATIC (FIXED VOLUME) NOT DYNAMIC (FLOW THROUGH)
- LIQUID NITROGEN (LN_2) AS THE “ENERGY METER”
  - SATURATED AT AMBIENT PRESSURE FOR STABILITY
- STEADY-STATE THERMAL EQUILIBRIUM
  - HEAT FLOW RATE IS THE SAME THROUGH ALL LAYERS
- TEMPERATURE RANGE FROM ABOUT 50 °C DOWN TO -196 °C
  - LARGE TEMPERATURE DIFFERENCE (ΔT)
  - DIFFERENT MEAN TEMPERATURES (T_M)
- MULTIPLE TEST POINTS FROM A SINGLE TEST

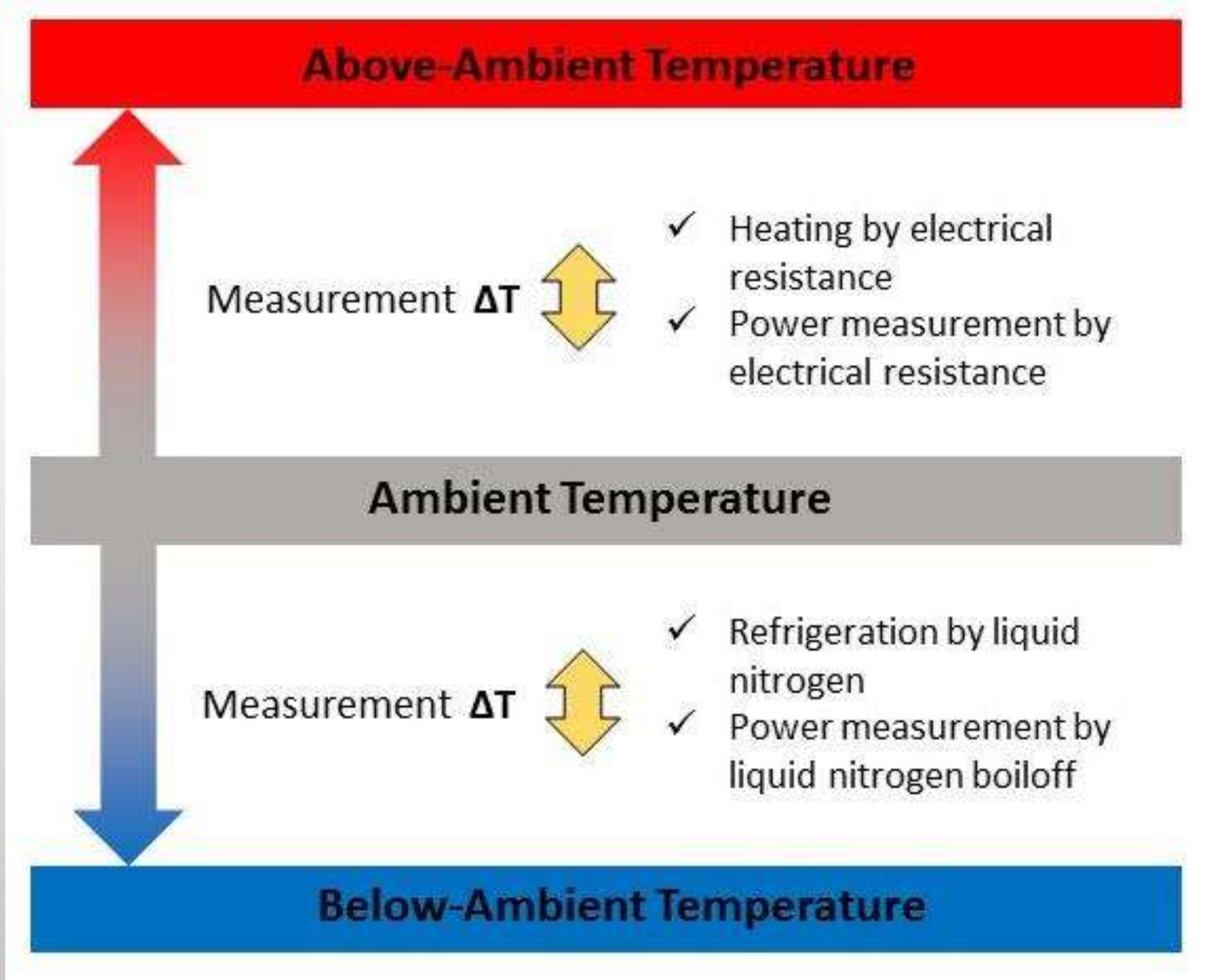
CONFIGURATIONS

- FLAT PLATE OR CYLINDRICAL
- HORIZONTAL CYLINDRICAL FOR PIPELINE INSULATION
- COMPARATIVE OR ABSOLUTE
- ASTM C1774 – *STANDARD GUIDE TO THERMAL PERFORMANCE TESTING OF CRYOGENIC INSULATION SYSTEMS*
  - THREE DIFFERENT APPROACHES: BOILOFF OR ELECTRICAL POWER
  - SIX DIFFERENT APPARATUSES: FOUR BOILOFF
  - X1.2 *The approaches, techniques, and methodologies given in this guide can be adapted for use in the cryogenic thermal performance testing of cryogenic pipelines: cryogen boiloff (static) or flow-through (dynamic).*
- ASTM C740 – *STANDARD GUIDE FOR EVACUATED REFLECTIVE CRYOGENIC INSULATION*
  - THERMAL PERFORMANCE DATA FOR MULTILAYER INSULATION (MLI) AND OTHER CRYOGENIC INSULATION SYSTEMS, FOAMS, AEROGELS, AND BULK-FILL MATERIALS

DEFINITIONS

- FROM ASTM C1774 AND ASTM C740 (NEW IN 2014)
- Effective thermal conductivity (k_e) — the thermal conductivity through the total thickness of the insulation test specimen between the reported boundary temperatures and in a specified environment (mW/m-K). The insulation test specimen may be one material, homogeneous non-homogeneous, or a combination of materials.
- System thermal conductivity (k_s) — the thermal conductivity through the total thickness of the insulation test specimen and all ancillary elements such as packaging, supports, getter packages, enclosures, etc. (mW/m-K).
- Heat flow rate (Q) — quantity of heat energy transferred to a system in a unit of time (W).
- Heat flux *(q)* — heat flow rate, under steady-state conditions, through a unit area, in a direction perpendicular to the plane of the thermal insulation system (W/m^2).

AMBIENT TEMPERATURE = 20 °C (±)

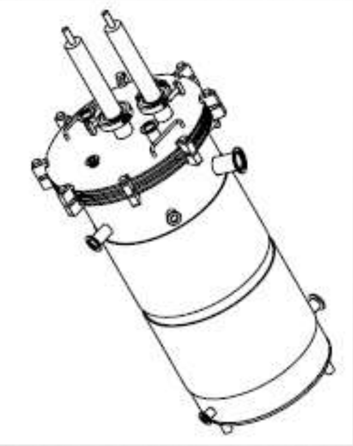


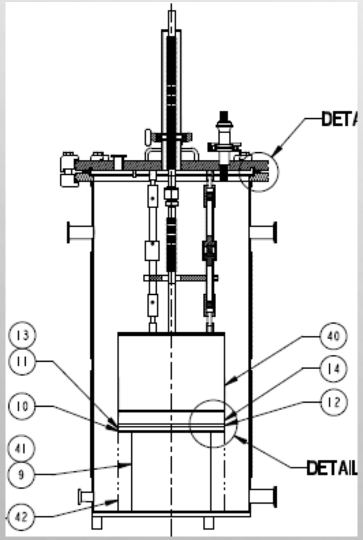
By interposing different insulation layers on the cold boundary, the cryogenic boiloff method is suitable for a wide range of below-ambient temperature applications.

STEADY-STATE BOILOFF

- ESTABLISH A STEADY WARM BOUNDARY TEMPERATURE (WBT) ON AN OUTER SURFACE.
- ESATABLISH A STEADY COLD BOUNDARY TEMPERATURE (CBT) ON AN INNER SURFACE.
- AFTER THERMALIZATION, THE HEAT FLOW RATE (Q) THROUGH THE INSULATION IS CONSTANT AND THE SAME THROUGH ALL INTERIOR LAYERS OF THE INSULATION SYSTEM.
- BY INTERPOSING A PRIMARY INSULATION LAYER ON THE INNER COLD BOUNDARY, THE CRYOGENIC BOILOFF METHOD IS USED FOR A WIDE RANGE OF BELOW-AMBIENT TEMPERATURE APPLICATIONS.

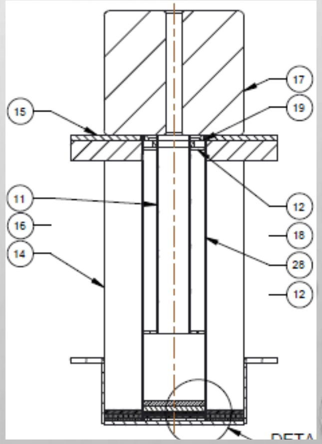
FLAT PLATE BOILOFF TESTING – CONFIGURATIONS





Insulation test cryostat instruments: flat-plate configuration.

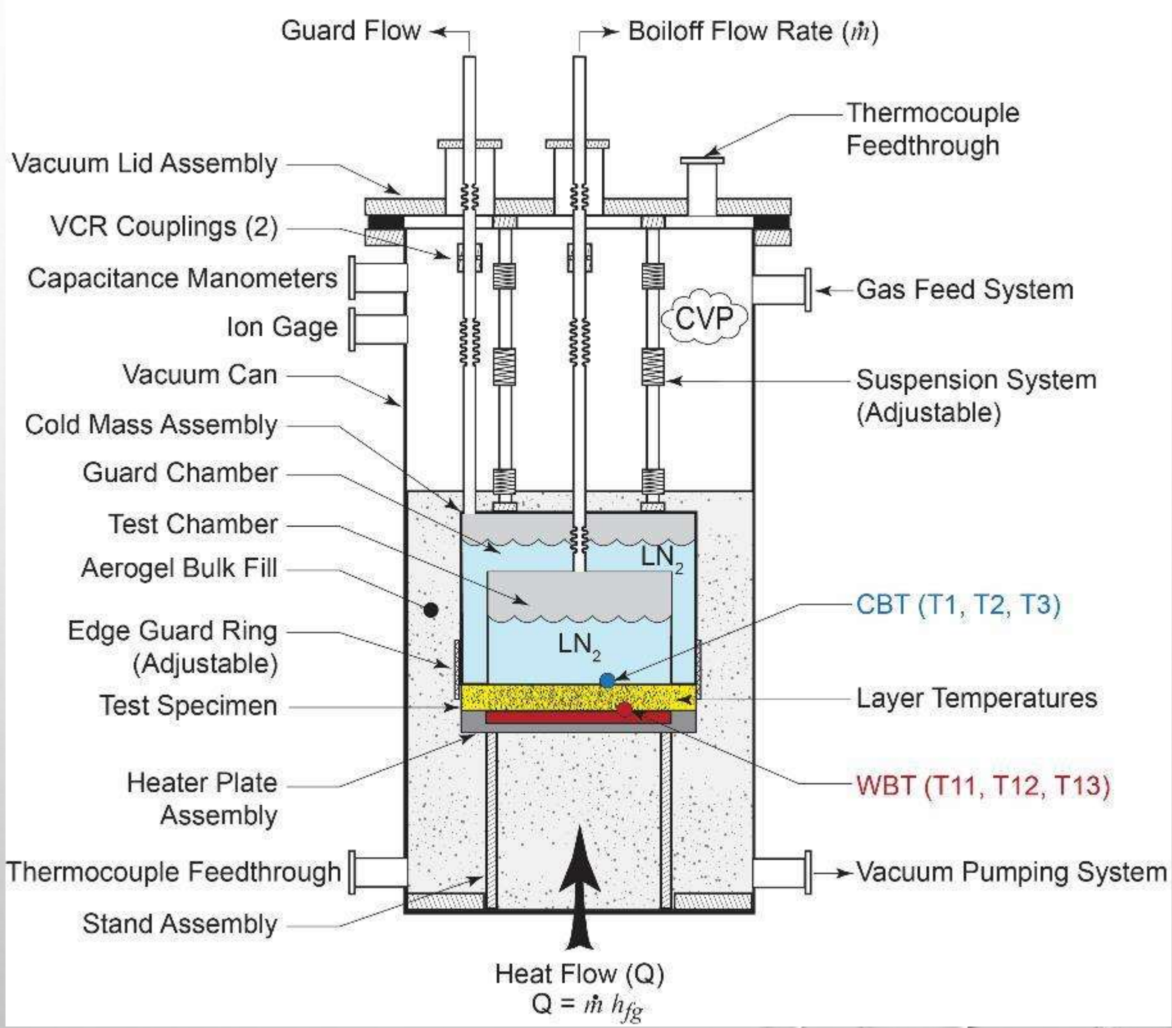
Instrument	Type	Test Specimen Size	ASTM Test Standard	Environment	Heat Flux (W/m^2)
Cryostat-500 (3 units)	Absolute	203 mm diameter, up to 40 mm thick	C1774 Annex A3	Full range vacuum 77 K–353 K	0.4–400
Cryostat-600 (1 unit)	Absolute w/structural element option	305 mm diameter, up to any thickness	C1774 Annex A3	Full range vacuum 77 K–353 K	0.4–400
Cryostat-400 (2 units)	Comparative	203 mm diameter, up to 40 mm thick	C1774 Annex A4	Full range vacuum 77 K–353 K	4–400
Macroflash Cup Cryostat (3 units)	Comparative	76 mm diameter, up to 7 mm thick	C1774 Annex A4	No vacuum 77 K–353 K	80–1000



FLAT PLATE BOILOFF TESTING – CRYOSTAT-500

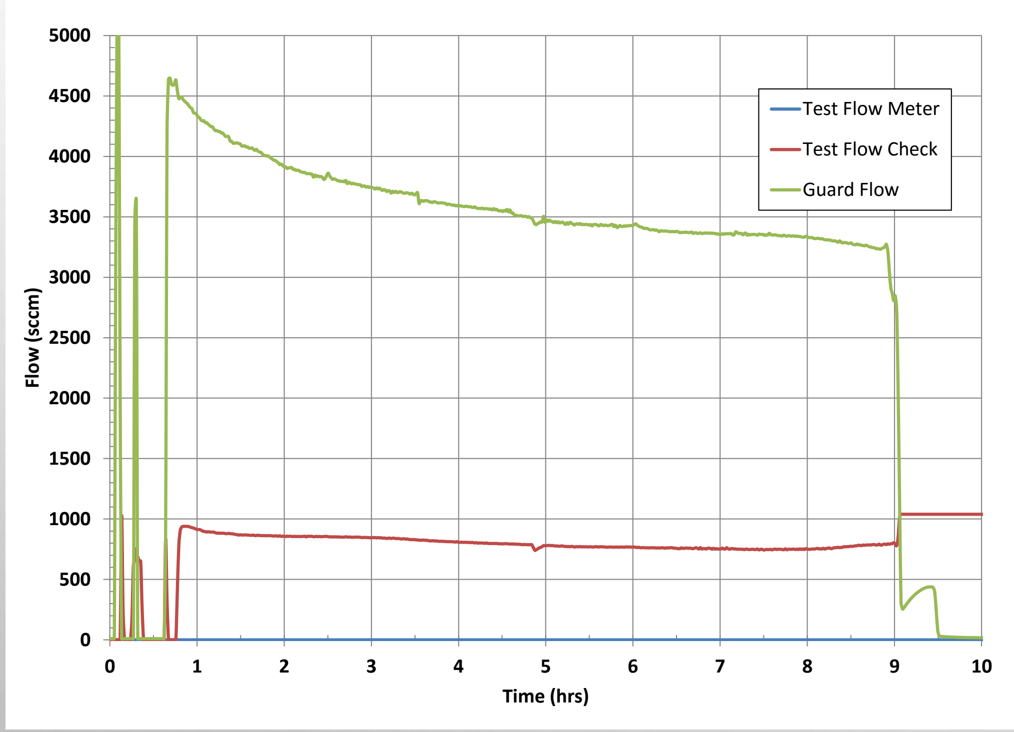
The Cryostat-500 insulation test instrument provides:

- ✓ Testing 204-mm diameter, 25-mm thick specimens under representative-use conditions.
- ✓ Direct energy rate measurement by LN_2 boiloff calorimetry.
- ✓ Reliable testing of non-homogenous, non-isotropic thermal insulation systems.
- ✓ **ASTM C1774, Annex A3**

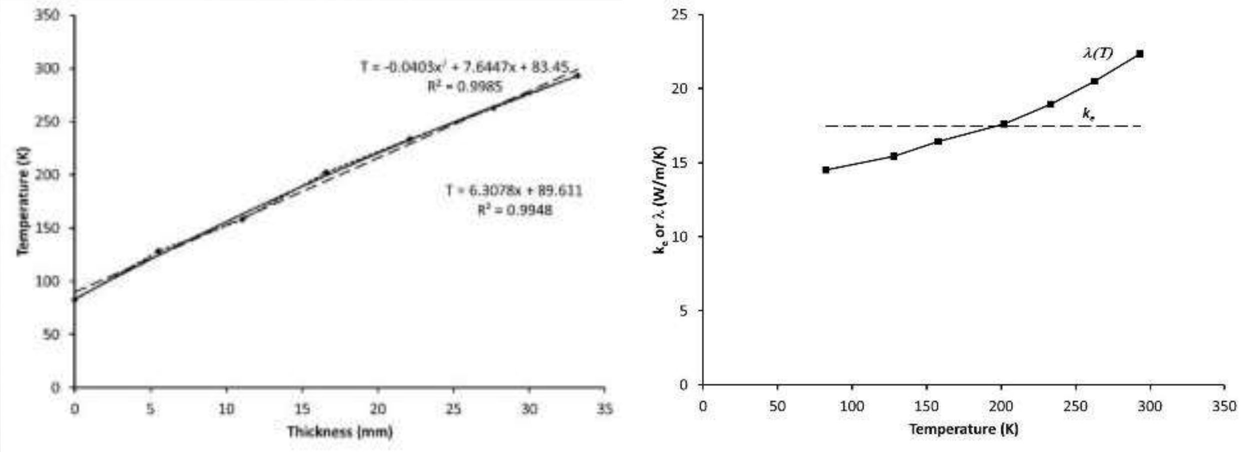


FLAT PLATE BOILOFF TESTING – EXAMPLE DATA

- ✓ For all flat plate calorimeters: over 500 materials specimens tested through approximately 2,100 individual tests representing over 6 years of continuous boiloff run time.
- ✓ Materials include, for example, composite panels, foams, aerogels, and MLI systems.

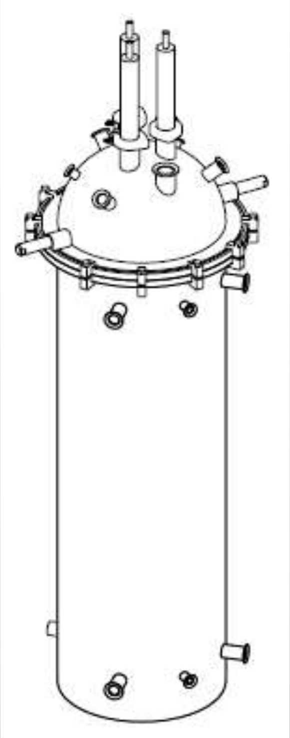


Boiloff flow rate for foam test specimen.



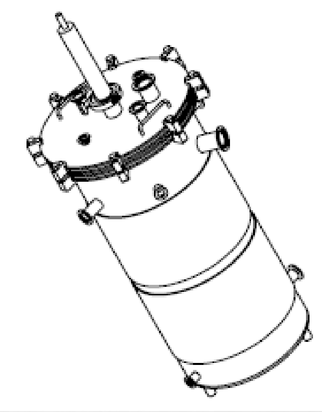
Temperature profiles measured through the thickness of a six-layer stack of aerogel blankets and the resulting effective thermal conductivity, k_e, and local thermal conductivity distribution, λ *(T)*.

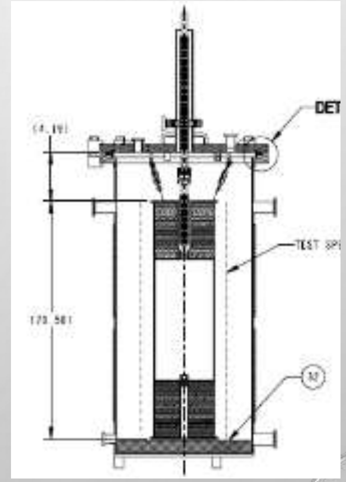
CYLINDRICAL BOILOFF TESTING – CONFIGURATIONS

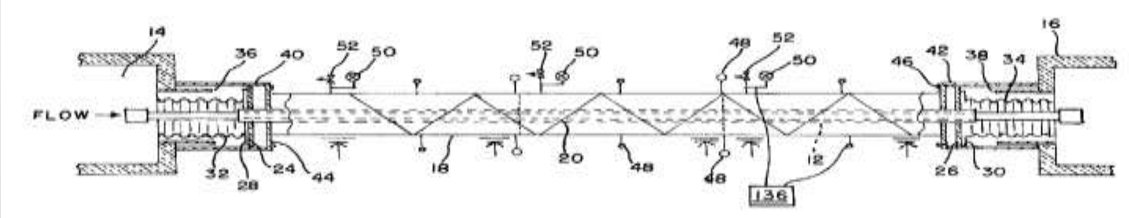


Insulation test cryostat instruments: cylindrical configurations.

Instrument	Type	Test Specimen Size	ASTM Test Standard	Environment	Heat Flux (W/m^2)
Cryostat-100 (1 unit)	Absolute	1 m long, 167 mm diameter, up to 50 mm thick	C1774 Annex A1	Full range vacuum 77 K–353 K	0.2–200
Cryostat-200 (2 units)	Comparative	0.5 m long, 132 mm diameter, up to 50 mm thick	C1774 Annex A2	Full range vacuum 77 K–353 K	1–200
Cryostat-P100 (1 unit)	Absolute	12.2 m long, 25 - 88 mm diameter up to 200 mm OD	C335	No vacuum or vacuum-jacket 77 K–353 K	4–400
Cryostat-P200 (future)	Comparative	1.8 m long, 33 mm diameter, up to 110 mm OD	C335	No vacuum 77 K–353 K	100–500



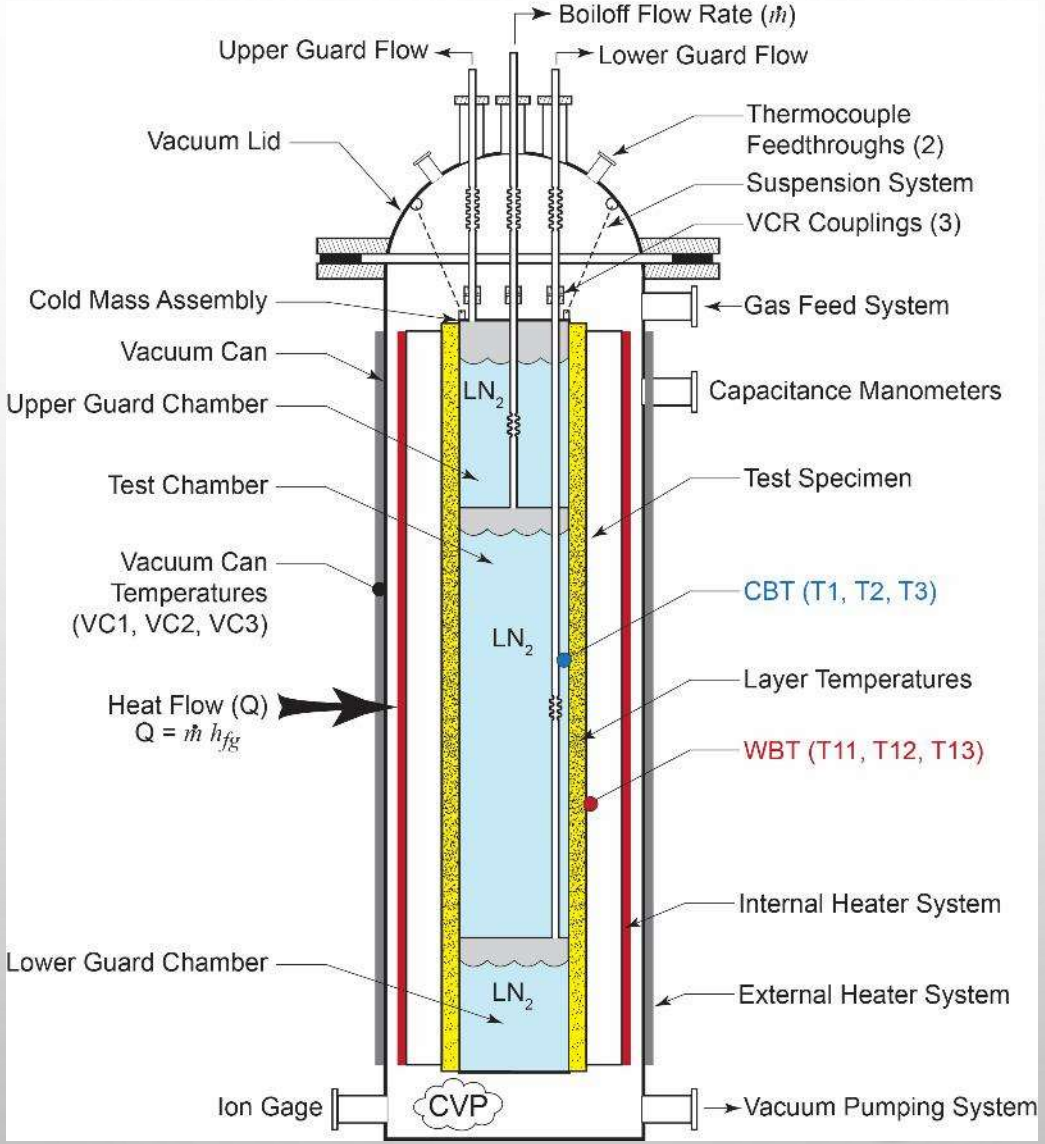




CYLINDRICAL BOILOFF TESTING – CRYOSTAT-100

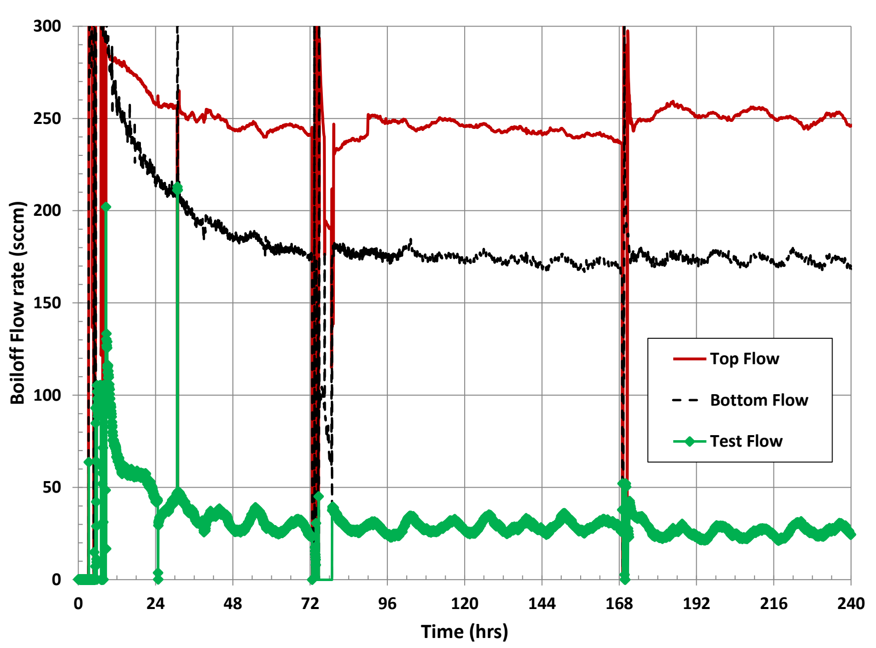
The Cryostat-100 insulation test instrument provides:

- ✓ Testing 1-meter long, 218-mm diameter specimens under representative-use conditions.
- ✓ Direct energy rate measurement by LN_2 boiloff calorimetry.
- ✓ Reliable testing of non-homogenous, non-isotropic thermal insulation systems.
- ✓ **ASTM C1774, Annex A1**

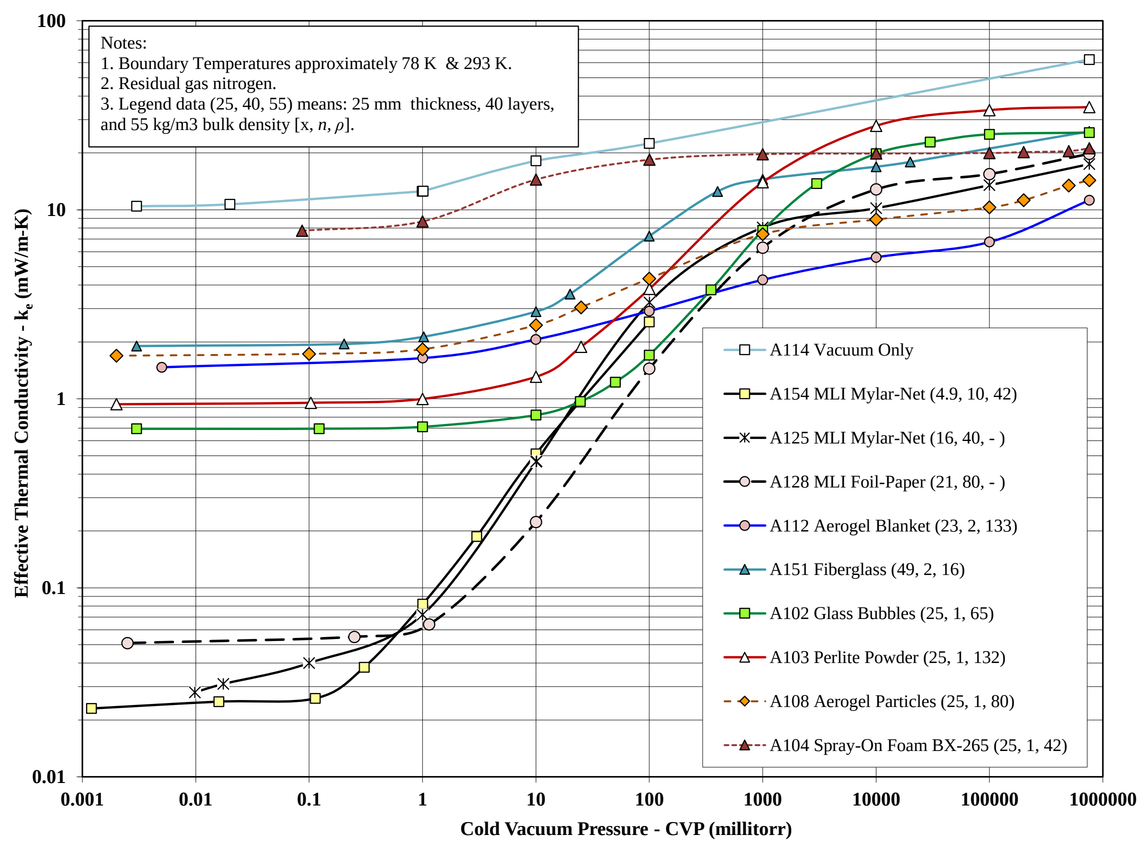


CYLINDRICAL BOILOFF TESTING – EXAMPLE DATA

- ✓ For all cylindrical calorimeters: grand total of 174 materials specimens tested through approximately 1,500 individual tests representing roughly 5 years of continuous boiloff run time.
- ✓ Baseline data for standards and benchmarks for comparison of thermal insulation materials.



Boiloff flow rate for MLI test specimen at high vacuum.



Summary of test results for various thermal insulation systems and materials: variation of k_e with vacuum pressure.

BELOW-AMBIENT INSULATED PIPE TESTING

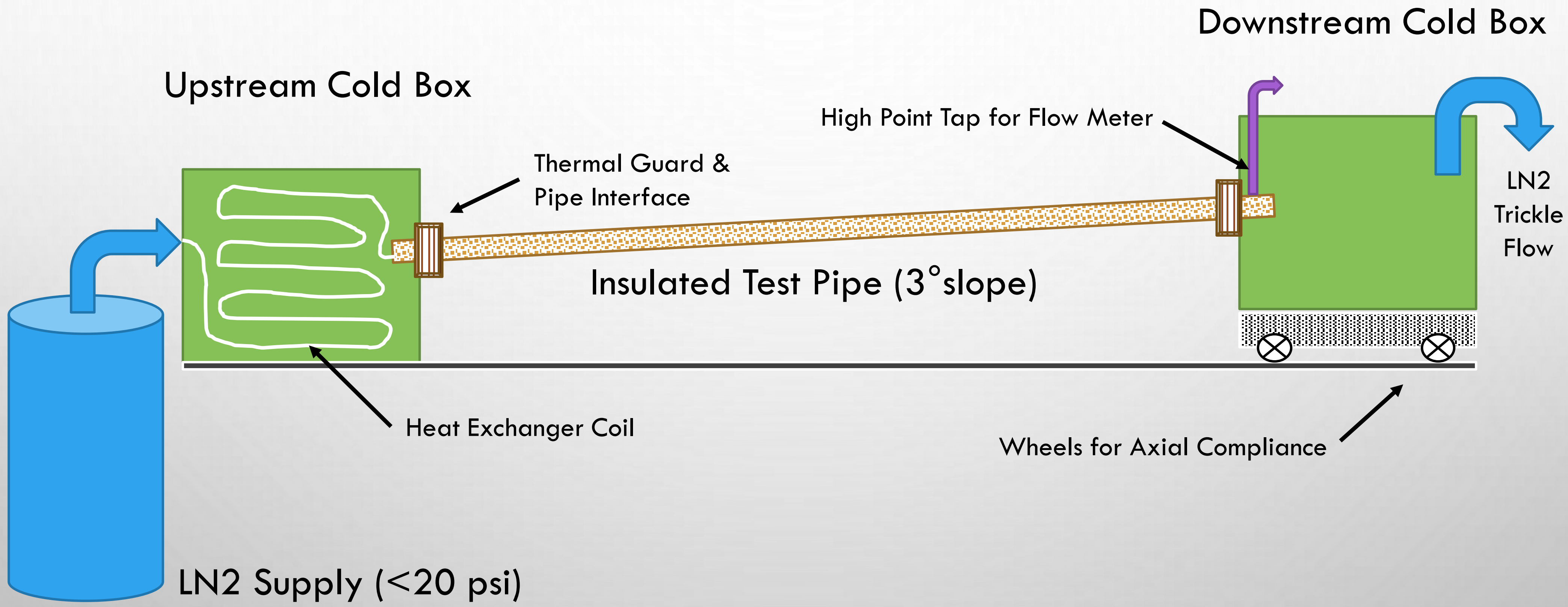
- REVISION OF ASTM C335 TO INCLUDE BELOW-AMBIENT METHOD BASED ON CRYOGENIC BOILOFF IS UNDER REVIEW BY C16 COMMITTEE OF ASTM INTERNATIONAL
- APPARATUS AND METHOD FOR THERMAL PERFORMANCE TESTING OF CRYOGENIC PIPING SYSTEMS HAS BEEN ESTABLISHED - CRYOSTAT-P100
    - ACCURATE HEAT LEAK DATA FOR FULL-SCALE PIPELINES UNDER "REAL WORLD" CONDITIONS
    - BASIS FOR STANDARDIZED HEAT TRANSFER TEST FOR LOW-TEMPERATURE PIPING SYSTEMS
- COMPARATIVE TYPE, BENCH-TOP COLD PIPE TESTER, CRYOSTAT-P200, IS UNDER DEVELOPMENT
- ENERGY-EFFICIENT TRANSFER LINES AND PIPING SYSTEMS FOR SPACE LAUNCH FACILITIES, EQUIPMENT, AND INDUSTRIAL INFRASTRUCTURE ARE THE TARGETS
- CURRENT WORK INCLUDES TESTING OF BELOW-AMBIENT THERMAL INSULATION MATERIALS/SYSTEMS
- EXAMPLE TEST DATA FOR DIFFERENT INSULATED PIPELINES (BOTH 18-M AND 12-M LENGTHS)

COLD PIPE TESTER - CRYOSTAT-P100

CURRENT 12-METER-LONG APPARATUS

- LN2 BOIL-OFF TEST APPARATUS, GUARDED, ABSOLUTE HEAT LEAK RATE
- 3 DEGREE UPWARD SLOPE TO PROVIDE HIGH POINT TAP FOR BOILOFF FLOW RATE
- EXTERNAL HEATER WRAP FOR WARM BOUNDARY TEMPERATURE CONTROL
- UPSTREAM AND DOWNSTREAM COLD BOXES FILLED WITH LN2
- TEST PIPES SUPPLIED WITH AMBIENT PRESSURE SATURATED LN2 VIA HEAT EXCHANGER COIL ROUTED THROUGH UPSTREAM COLD BOX
- TEMPERATURE MEASUREMENTS:
  - LENGTH-WISE: TOP, SIDE, AND BOTTOM
  - THROUGH THICKNESS OF INSULATION
  - TERMINATIONS
- TWO TEST ARTICLES (TYPICAL):
  - 12-M LONG (40-FEET)
  - UP TO 3-INCH DIAMETER PIPE SIZE (NPS)
  - TESTED IN PARALLEL

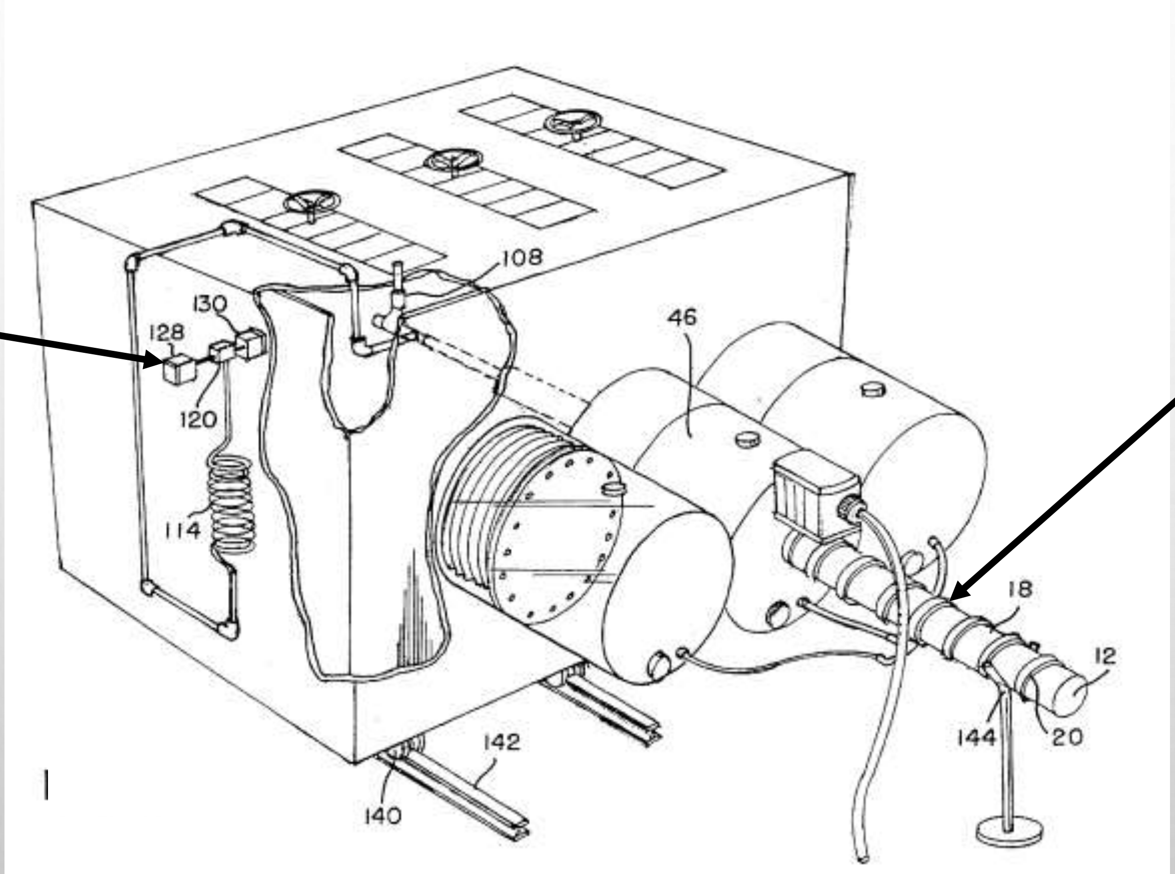
COLD PIPE TESTER - CRYOSTAT-P100



COLD PIPE TESTER - CRYOSTAT-P100

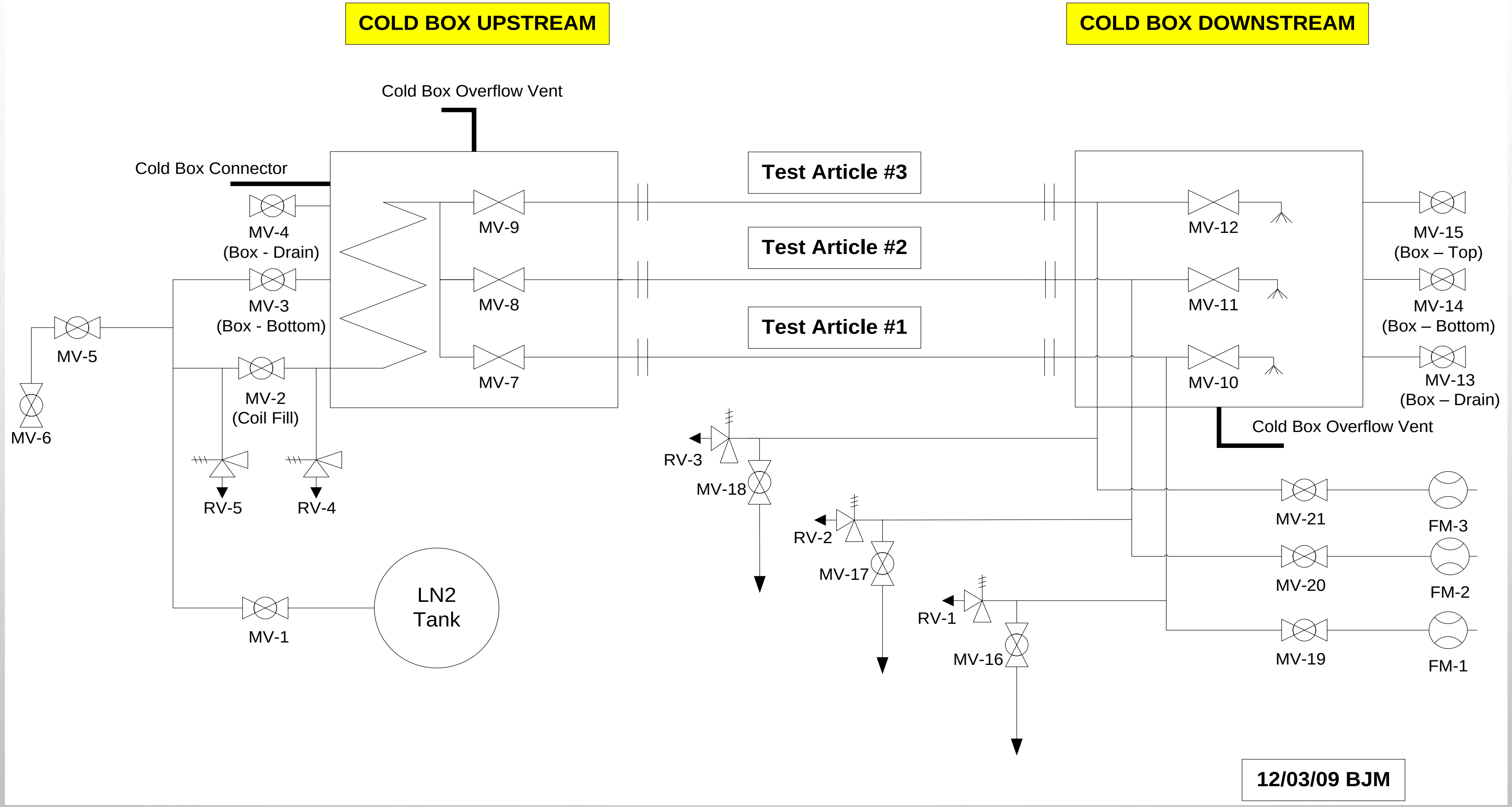
Downstream Cold Box assembly showing insulated test pipe connection

Boiloff Flow Meter connection



External Heater Wrap

COLD PIPE TESTER - CRYOSTAT-P100



COLD PIPE TESTER - CRYOSTAT-P100

Thermal End Guards & Test Pipe Termination

Notes:

- ✓Adaptable to any end connections.
- ✓Terminations are thermally guarded.
- ✓Built-in compliance for thermal contraction.
- ✓Center line is used for downstream cold box supply.

COLD PIPE TESTER - CRYOSTAT-P100

PHASES:

- ✓ COOLDOWN
- ✓ FILL
- ✓ COLD SOAK
- ✓ TEST RUNS
- ✓ REFILL
- ✓ DRAIN

MULTIPLE TEST RUNS ARE PERFORMED AFTER COLD SOAK PHASE

COLD PIPE TESTER - CRYOSTAT-P100

SUMMARY OF TEST RESULTS: 3" NOMINAL PIPE WITH 1.5" THICK INSULATION CLAM-SHELLS

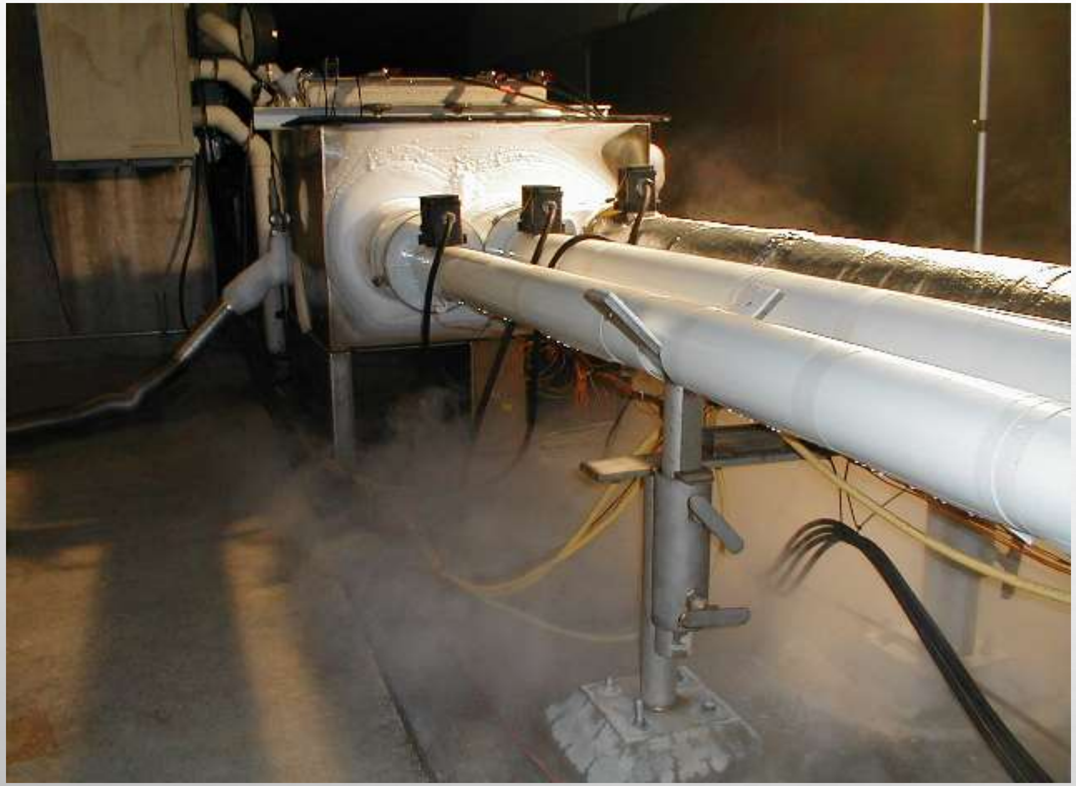
	East Pipeline	**West Pipeline**
Total heat leakage rate	30.0 W	32.0 W
Heat leak per unit length	2.45 W/m	2.62 W/m
Overall k-value (k_{oafi})	0.95 mW/m-K	1.1 mW/m-K
Boil-off flow rate	7.25 slpm	7.73 slpm

Notes:

- ✓Boundary temperatures are approximately 293 K and 78 K.
- ✓Cold soak phase of approximately 24 hours.
- ✓Cold vacuum pressures verified.
- ✓Wind and solar influences are negligible (vacuum jacketed insulation system).

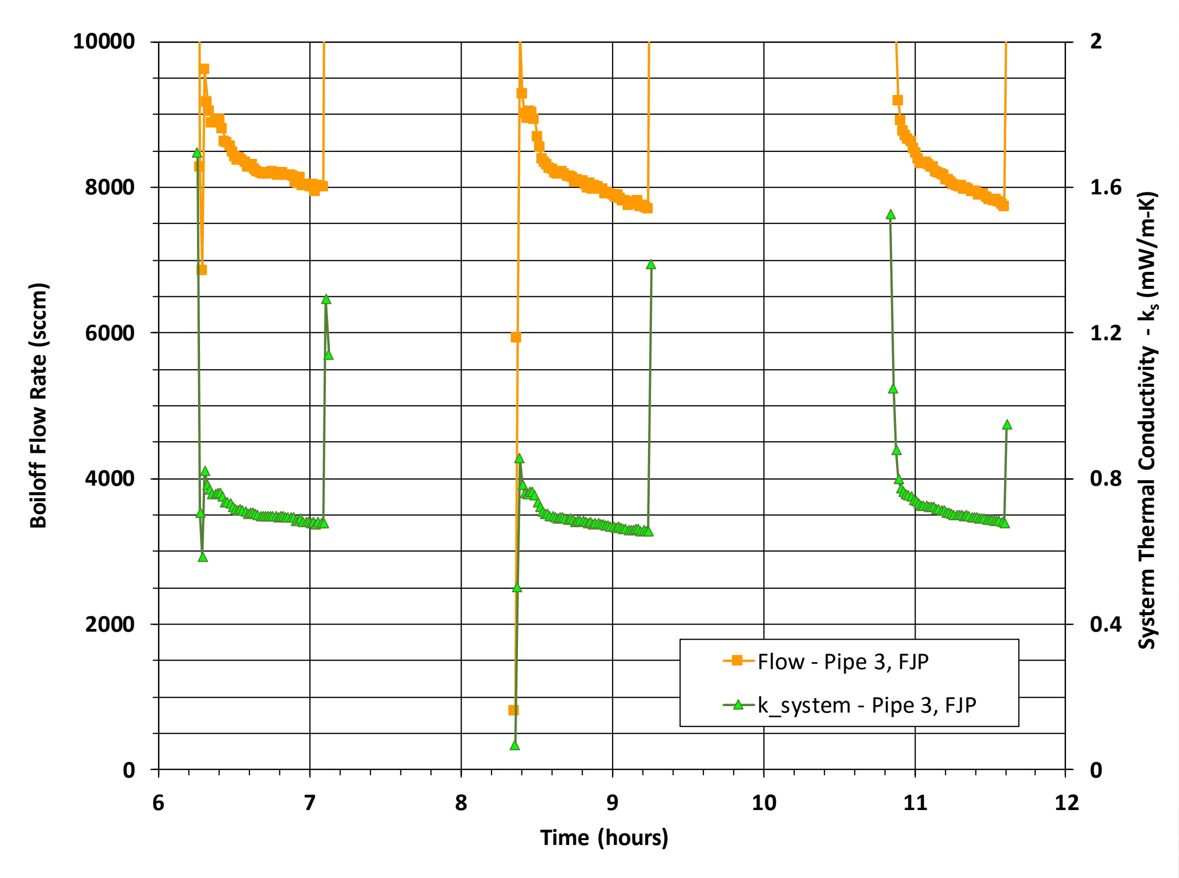
COLD PIPE TESTER - CRYOSTAT-P100

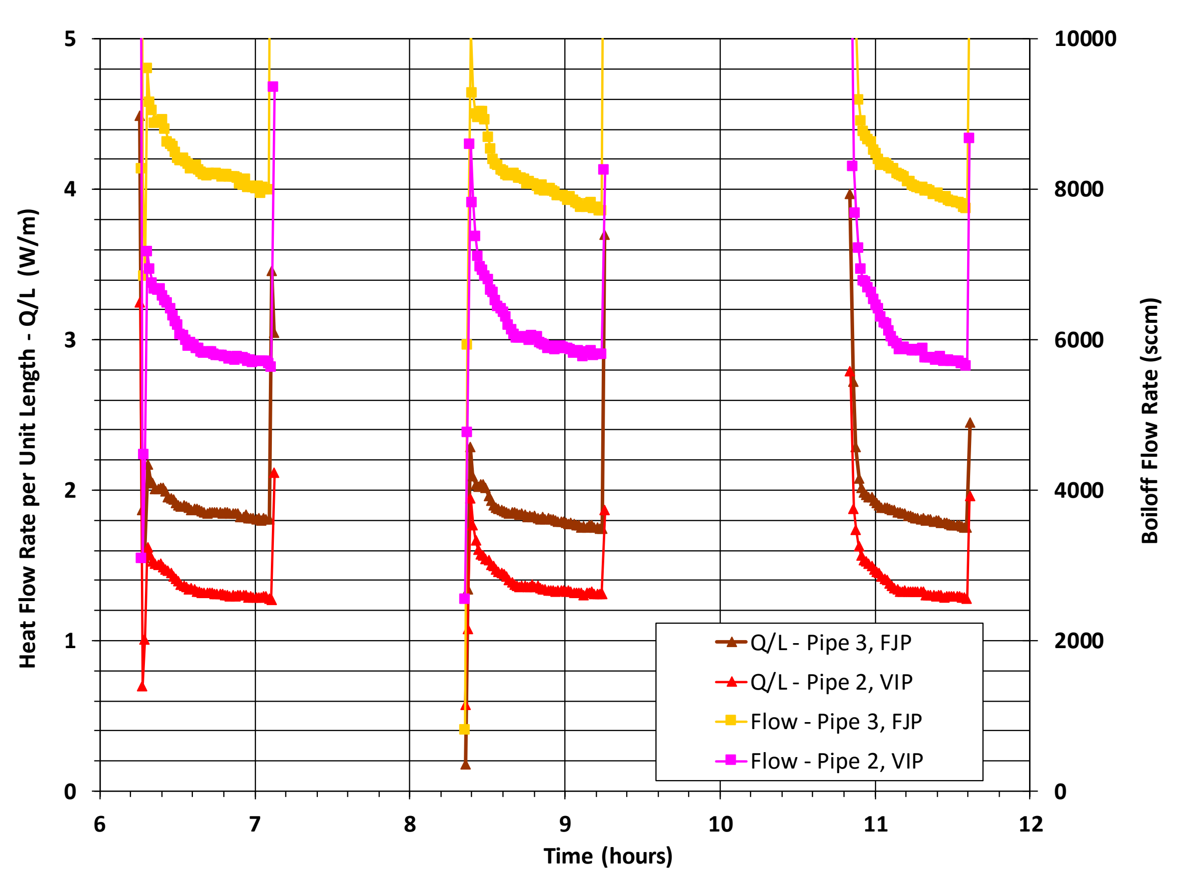
ORIGINAL 18-METER-LONG APPARATUS



COLD PIPE TESTER - CRYOSTAT-P100

Example test results for cryogenic-vacuum pipelines: VIP (Pipe 2) and FJP (Pipe 3)





OTHER EXAMPLES OF COLD PIPE TESTING

NOT COMPLICATED

COMPLICATED

UNCERTAINTY ANALYSIS: CRYOSTAT-100

- TOTAL UNCERTAINTY IN k_e IS CALCULATED TO BE 3.4% FOR THE CRYOSTAT-100:
  - UNCERTAINTY IN HEAT FLUX Q IS 3.2% (TEMPERATURES ARE NOT PART OF THE HEAT FLUX CALCULATION).
  - PHYSICAL MEASUREMENT OF TEST SPECIMEN IS “ROBUST” BECAUSE ONLY THE OUTER DIAMETER, NOT THICKNESS, IS PART OF THE CALCULATION.
- OVERALL ERROR OF k_e ESTIMATED FOR THE WORST-CASE SITUATION. HEAT OF VAPORIZATION OF LN2 IS THE LARGEST SOURCE OF UNCERTAINTY AND IS TAKEN TO BE 2% ERROR.
- ALL HEAT FLOW IS ASSUMED TO GO INTO VAPORIZING THE LIQUID. THE VAPOR HEATING EFFECT CAN BE NEGLECTED FOR LN2 CALORIMETERS WITH SMALL ULLAGE SPACES (ERROR IS LESS THAN 0.1%).
- REPEATABILITY FOR MOST TESTS IS DEMONSTRATED TO BE WITHIN 2%.

UNCERTAINTY ANALYSIS: CRYOSTAT-100

$$Q = V_{STP}\rho_{STP}h_{fg}\left(\frac{\rho_f}{\rho_{fg}}\right)$$

$$k_e = \frac{Qx}{A_e \Delta T} = \frac{Q\ln\left(\frac{d_o}{d_i}\right)}{2\pi L_e \Delta T}$$

$$q = \frac{Q}{A_e}$$

Symbols and sources of error for the cylindrical calorimeter, Cryostat-100.

Symbol	Description	Unit	% Error
V	Volumetric flow rate (boiloff) at STP	m^3/s	0.500
ρ	Density of GN_2 (boiloff) [0.0012502 g/cm^3]	kg/m^3	n/a
h_{fg}	Heat of vaporization	J/g	2.37
d_o & d_i	Outer and inner diameters of insulation specimen	m	1.53 & 1.23
x	Thickness of insulation specimen	m	n/a
L_e	Length, effective heat transfer	m	0.730
A_e	Area, effective heat transfer area	m^2	n/a
ΔT	Temperature difference *(WBT – CBT)*	K	0.894

Measurement of the boiloff flow rate is made using a mass flow meter that automatically compensates for gas densities in the range of 273 K to 323 K. The mass flow meter output is in terms of a volumetric flow rate at STP (0 °C and 760 torr).

FUTURE PLANS

- CONTINUE WORK WITH INDUSTRY PARTNERS FOR TECHNICAL CONSENSUS STANDARD FOR BELOW-AMBIENT THERMAL PERFORMANCE TESTING OF INSULATED PIPING
    - ABOVE-AMBIENT TEST STANDARD COMPATIBILITY
    - REVISE ASTM C335 OR NEW STANDARD?
- DEVELOP COMPARATIVE, BENCH-TOP CRYOSTAT-P200 FOR 1.5-METER LONG 25-MM DIAMETER (NOMINAL) TEST PIPE
- VERIFY CONSISTENT TECHNIQUES FOR COLD BOUNDARY TEMPERATURES UP TO APPROXIMATELY 0° C
- ROUND ROBIN TESTING OF SELECT INSULATION MATERIAL(S)

CONCLUSION

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REFERENCE PUBLICATIONS

- FESMIRE, J.E., "STANDARDIZATION IN CRYOGENIC INSULATION SYSTEMS TESTING AND PERFORMANCE DATA," PHYSICS PROCEDIA 67, 1089 – 1097 (2015).
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